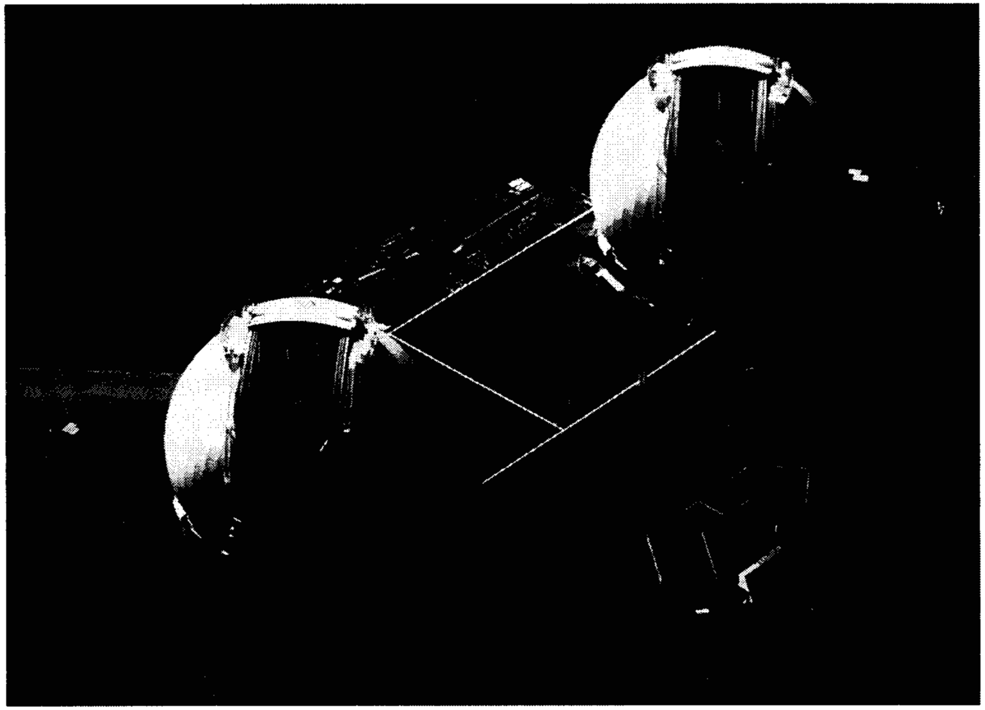
Jet Propulsion Laboratory
California Institute of Technology

W.M. Keck Observatory
California Association for Research in Astronomy

National Aeronautics and Space Administration



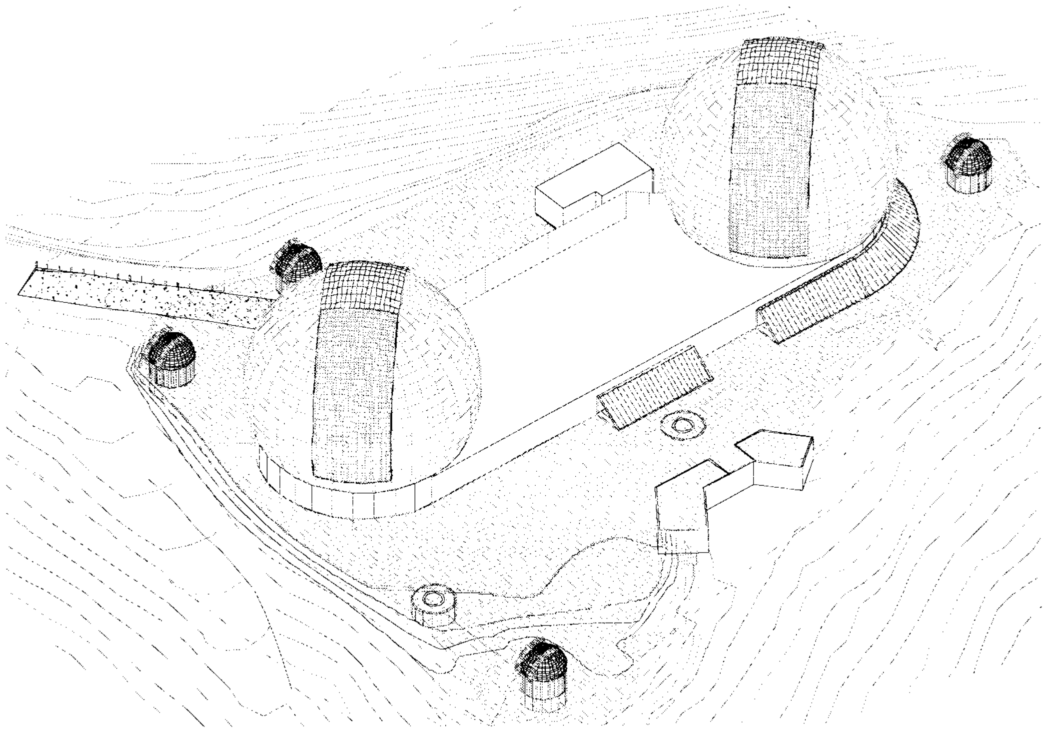
Overview of the Keck Interferometer

Dr. Gerard van Belle, JPL

2 March 1999, VLT Opening Symposium

http://huey.jpl.nasa.gov/keck

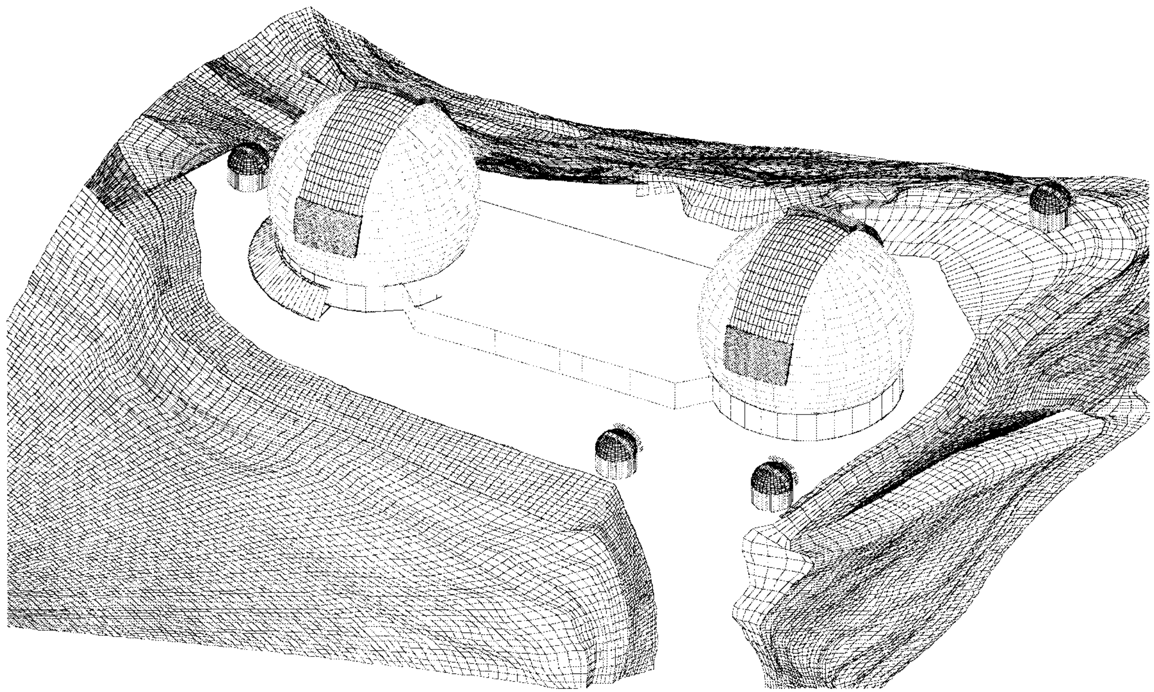
Outline



- Introduction
- Science with Keck Interferometer
- Instrument description
- Observing approach

Keck Interferometer

- Interferometry with the two 10-m Keck telescopes on Mauna Kea and four 1.8-m outrigger telescopes
- NASA-funded joint project between JPL and CARA
- Five-year development; funding starting FY98
- Broad range of science capabilities



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Palomar Testbed Interferometer

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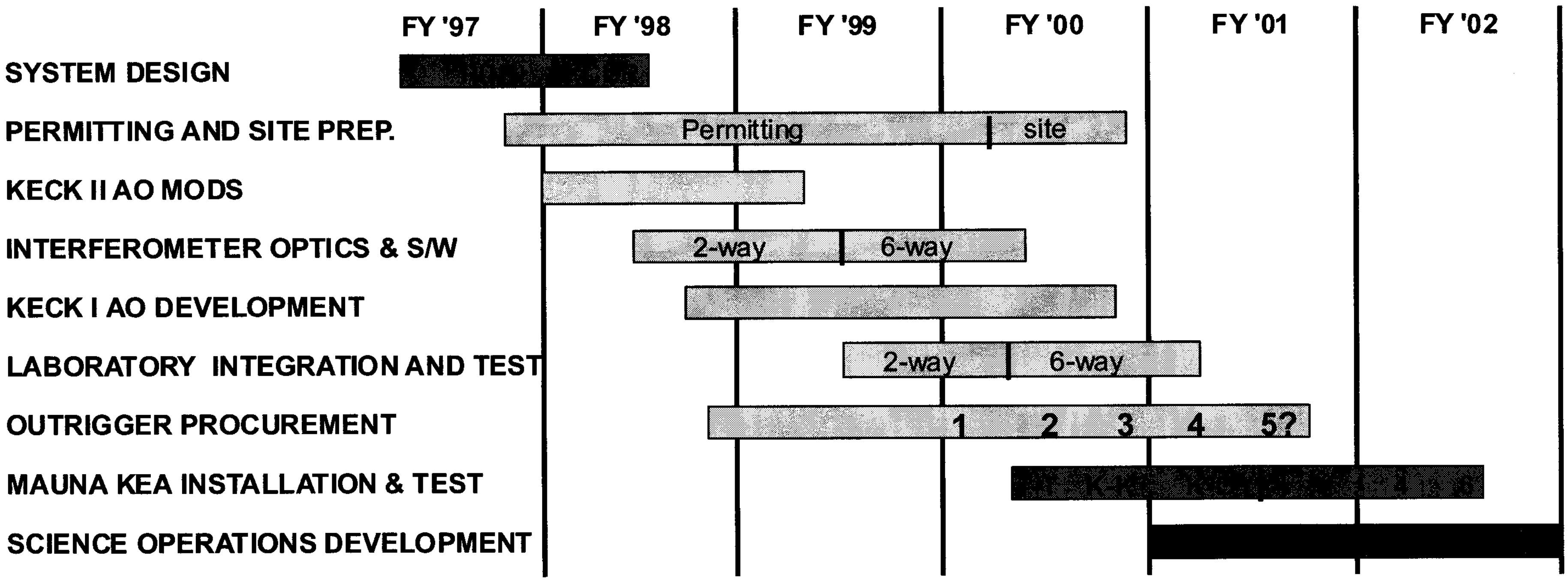
Schedule



Key features

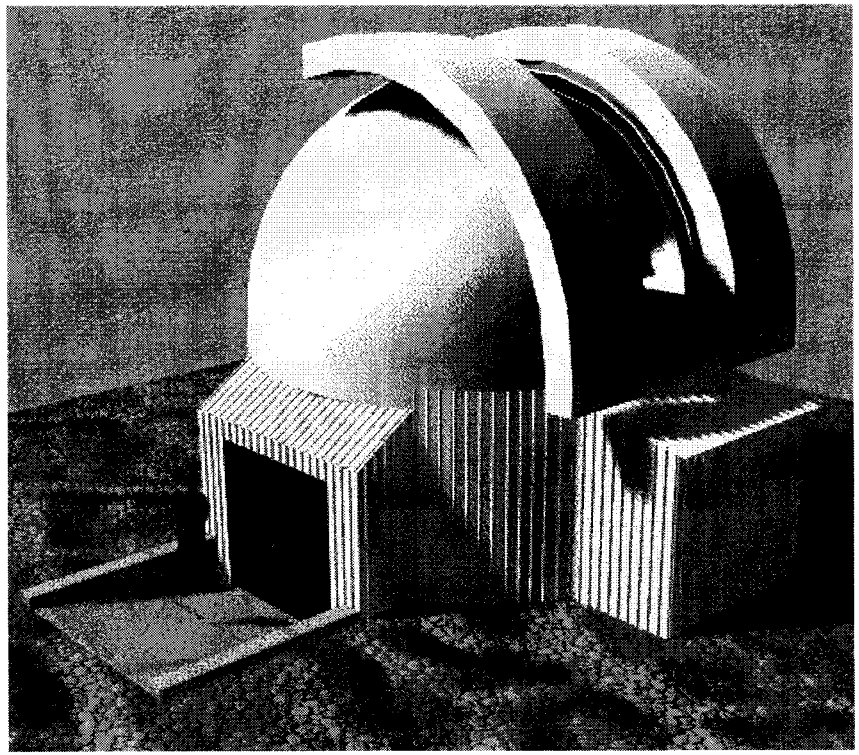
- Michelson combination among two 10-m Kecks and four 1.8-m outriggers
  - Keck-Keck baseline: 85 m
  - Outrigger-outrigger baseline: 25 m (min) / 140 m (max)
- Phasing with adaptive optics and fast tip/tilt correction
- Cophasing with fringe detection/tracking and active delay lines
  - Dual-star feeds at each telescope
- Back-end instruments
  - Two-way beam combiners at 1.6--2.4 μm for fringe tracking (cophasing), astrometry, and imaging
  - Multi-way imaging combiner at 1.6--5 μm and 10 μm
  - Nulling combiner at 10 μm

Science using the two Kecks

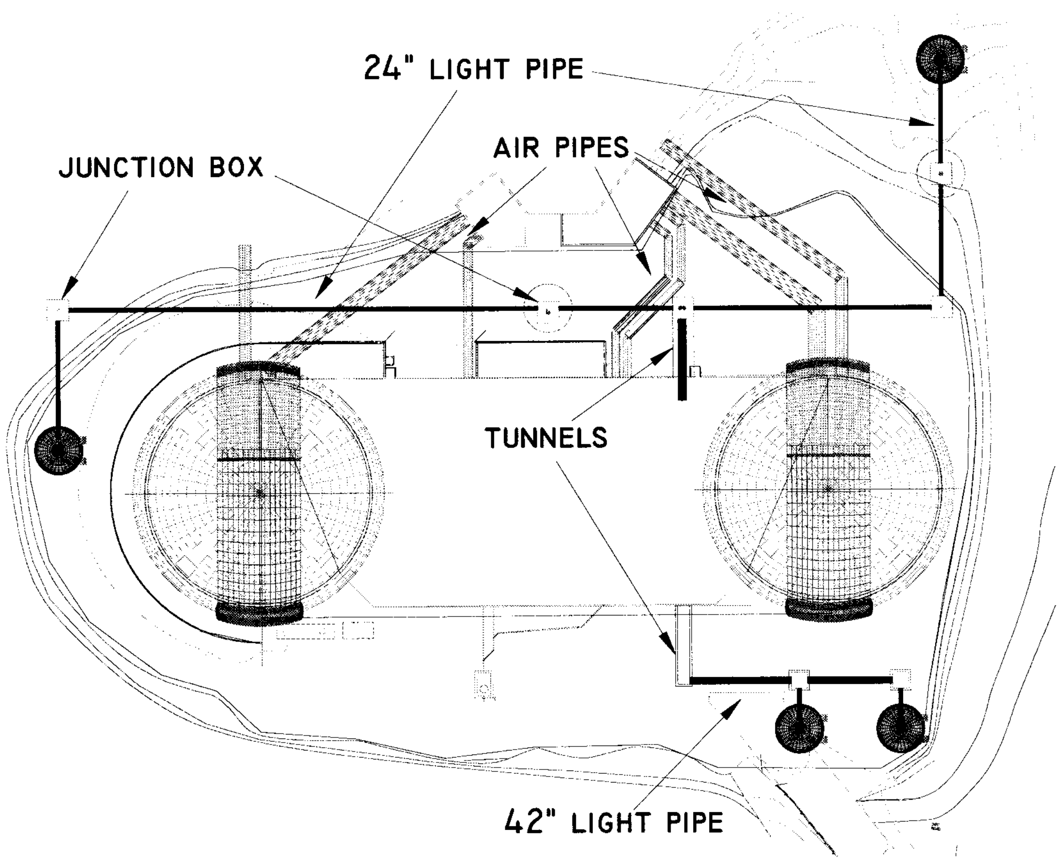
- Detection of hot Jupiters
  - Uses two-color differential-phase technique
- Characterization of exozodiacal dust
  - Survey a number of nearby systems for integrated exozodiacal emission at 10 μm
  - Important for Terrestrial Planet Finder (TPF) mission planning
- High sensitivity parametric imaging

Science enabled by the outriggers

- Astrometric search for planets
  - Survey 100's of nearby stars for planets to Uranus mass
  - Uses outrigger telescopes for long-term survey
- Imaging with 6-element array
  - Good (u,v)-plane coverage
  - 9 of 15 baselines include a 10-m telescope
    - » Background-limited sensitivity equivalent to two 4.4-m's
    - » Other imaging options using 1 Keck with outriggers, or just outriggers



Site plan



- 4 outrigger telescopes
- 2 additional outrigger pads (for future expansion)
- Underground pipes for light propagation to Keck basement

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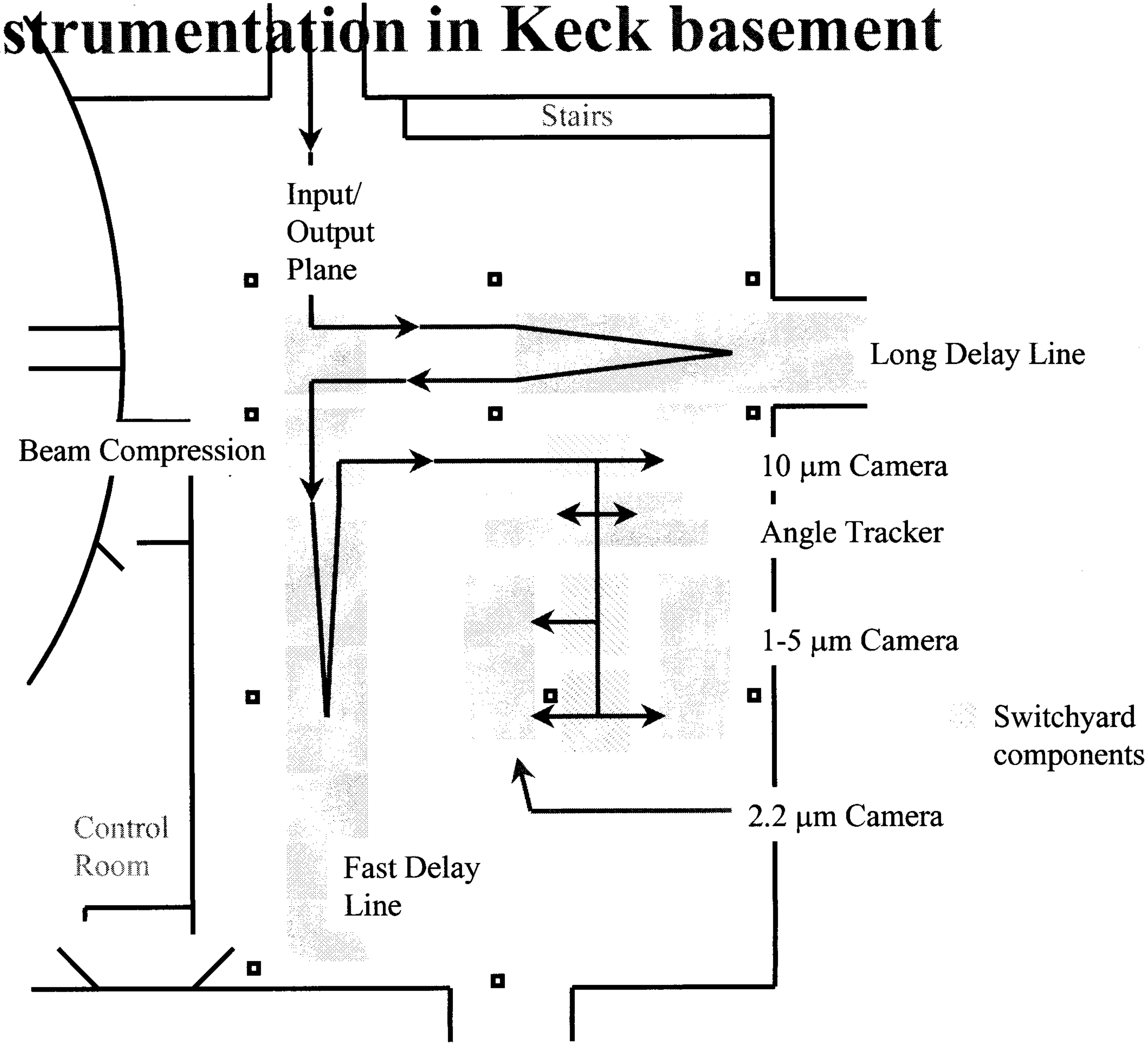
Instrumentation in Keck basement



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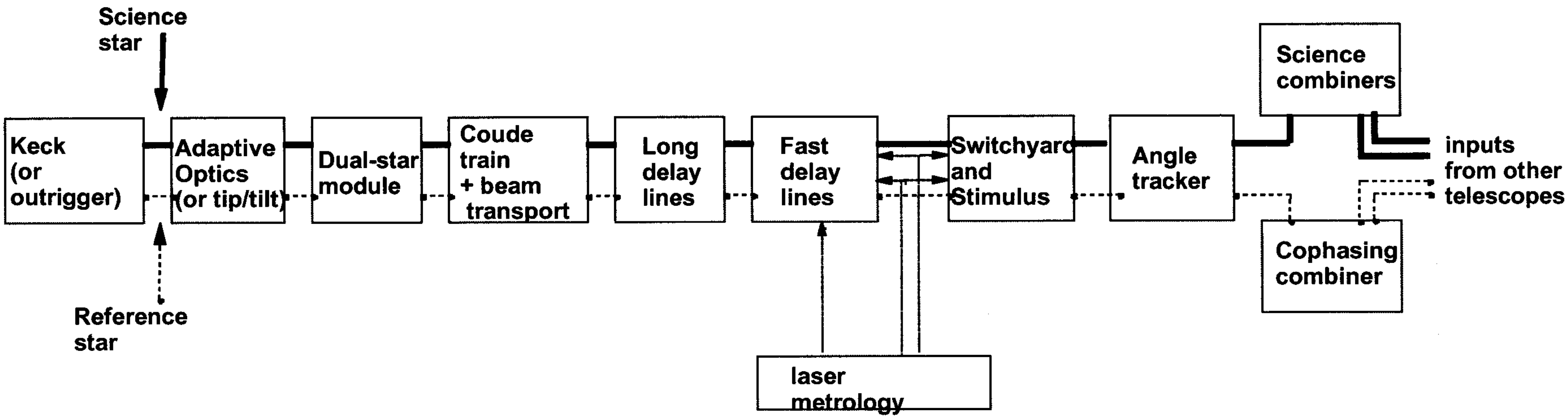
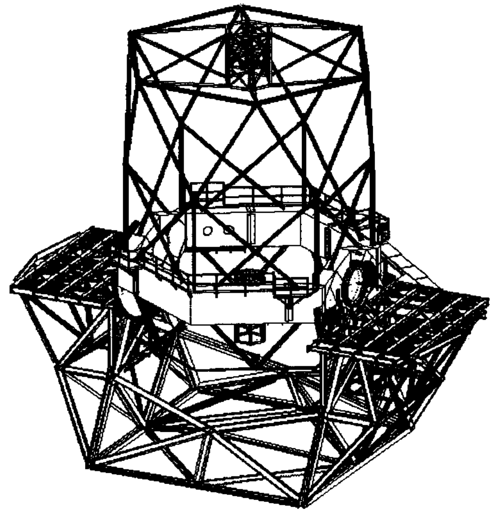
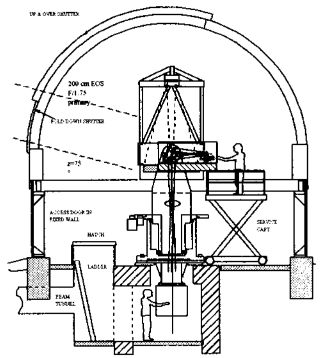
Keck Interferometer Beam Train



Telescopes

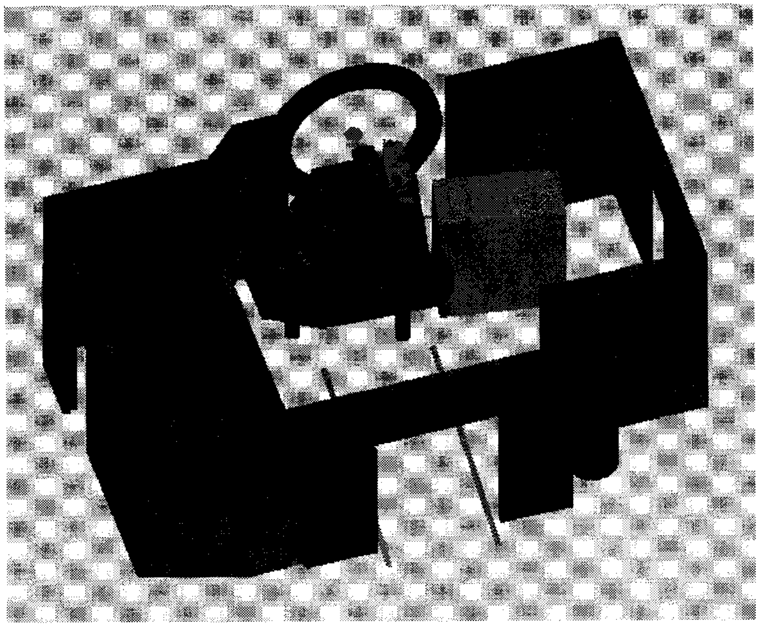
- Two 10-m Keck telescopes
  - 85-m Keck-Keck baseline
- Four 1.8-m outrigger telescopes
  - Used with Kecks for imaging
  - Used separately for astrometry
  - Key specifications
    - » 10-cm collimated output (after DSM)
    - » Stable pivot for astrometry
- For instrument debugging, 40-cm siderostats (like on PTI) will be used





Wavefront Correction

- **Adaptive optics on the Kecks**
  - NGS + LGS AO on K2
  - Add new system for K1
  - Minor mods needed to accommodate interferometry



- **Tip/Tilt correction on outriggers**
  - Fast tip/tilt is adequate for near-IR operation
  - Correction via active secondary
  - Sensing in beam-combining lab

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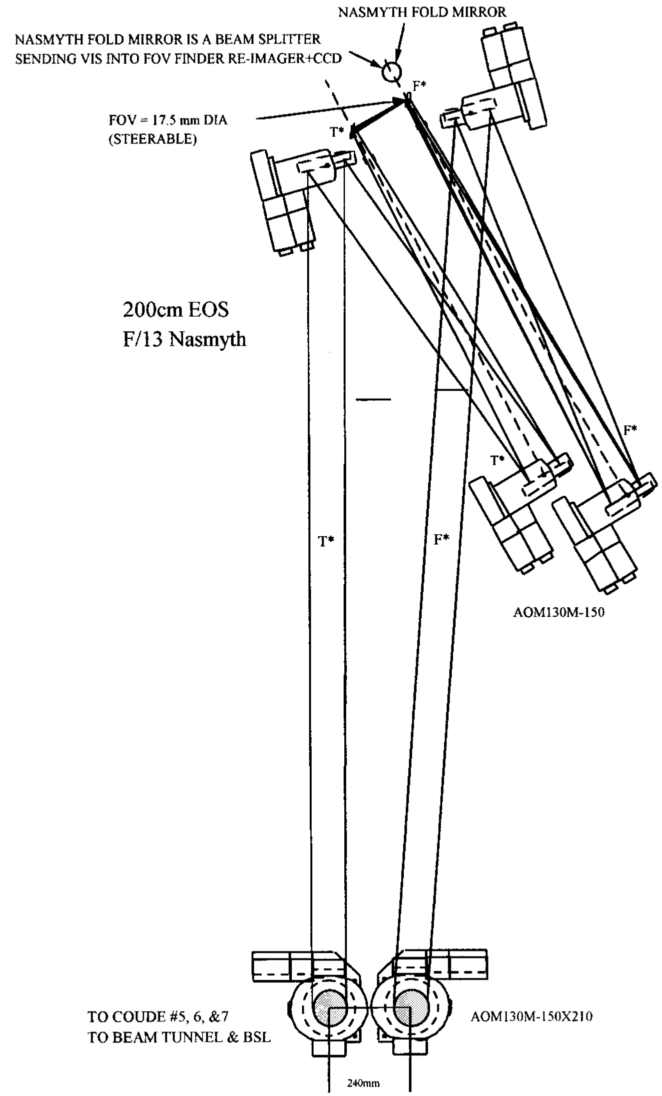
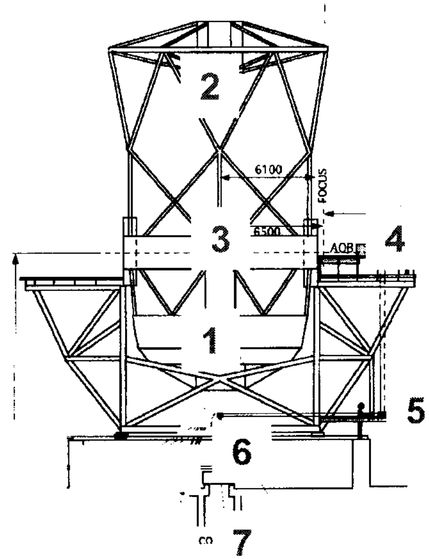
Dual-star module (DSM)

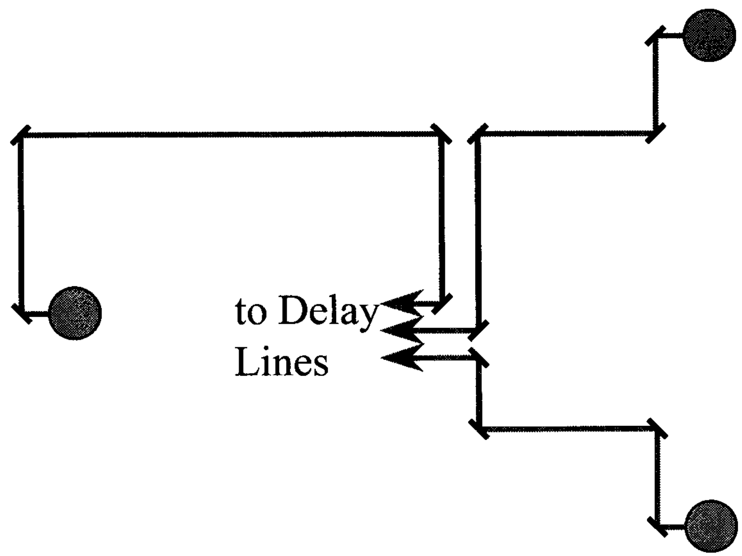
- Separates and tracks primary and secondary stars for cophasing and astrometry
- Produce two collimated beams to feed coude train
- DSM for Kecks slides in like NIRSPEC



Coude Train and Beam Transport

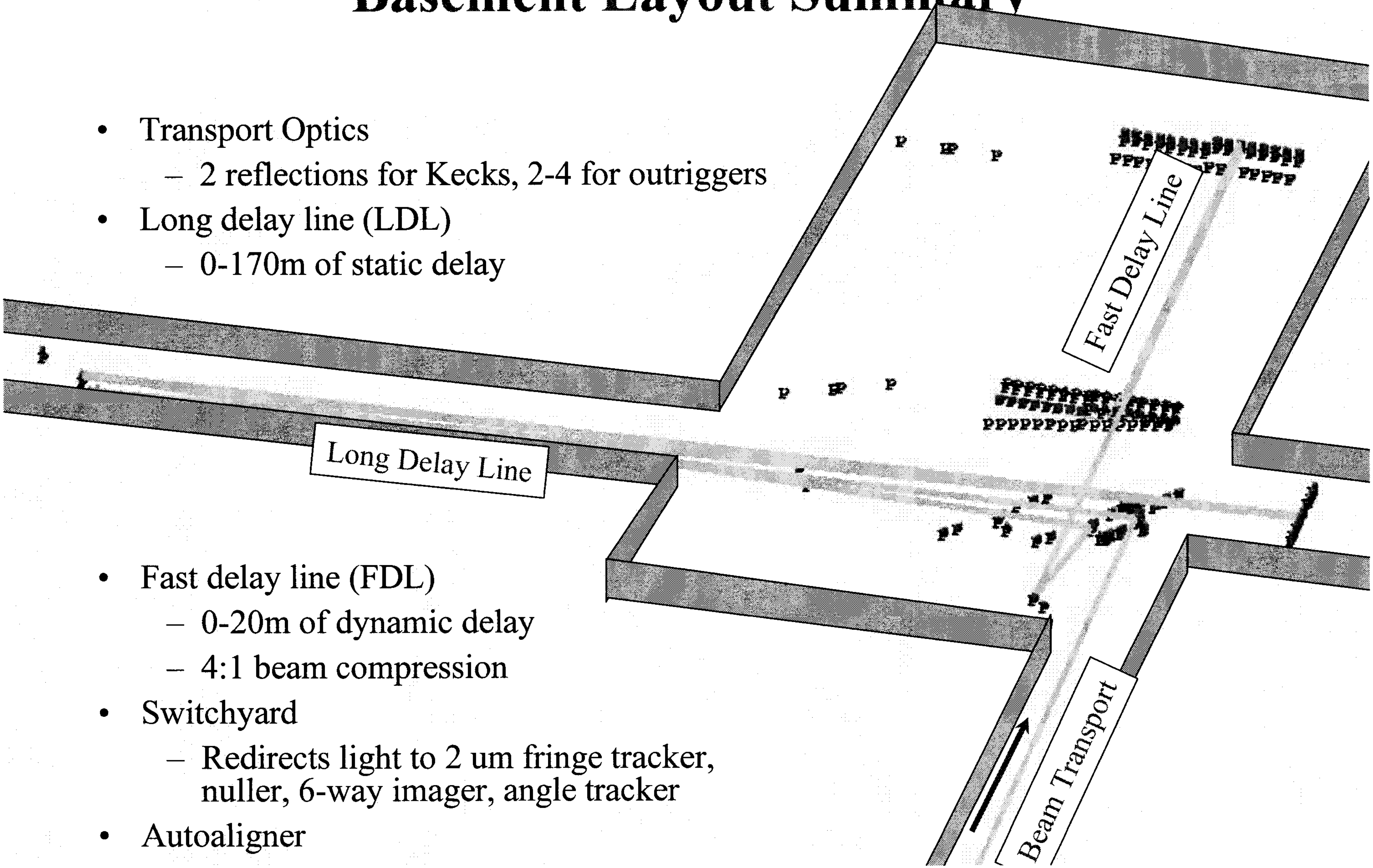
- Keck coude train needs to be completed to bring light from DSM to base of telescope (M7)
  - Also need to derotate secondary beam
- Similar coude needed on outriggers
- Beam transport system routes light from M7 to delay lines in interferometry lab





Basement Layout Summary

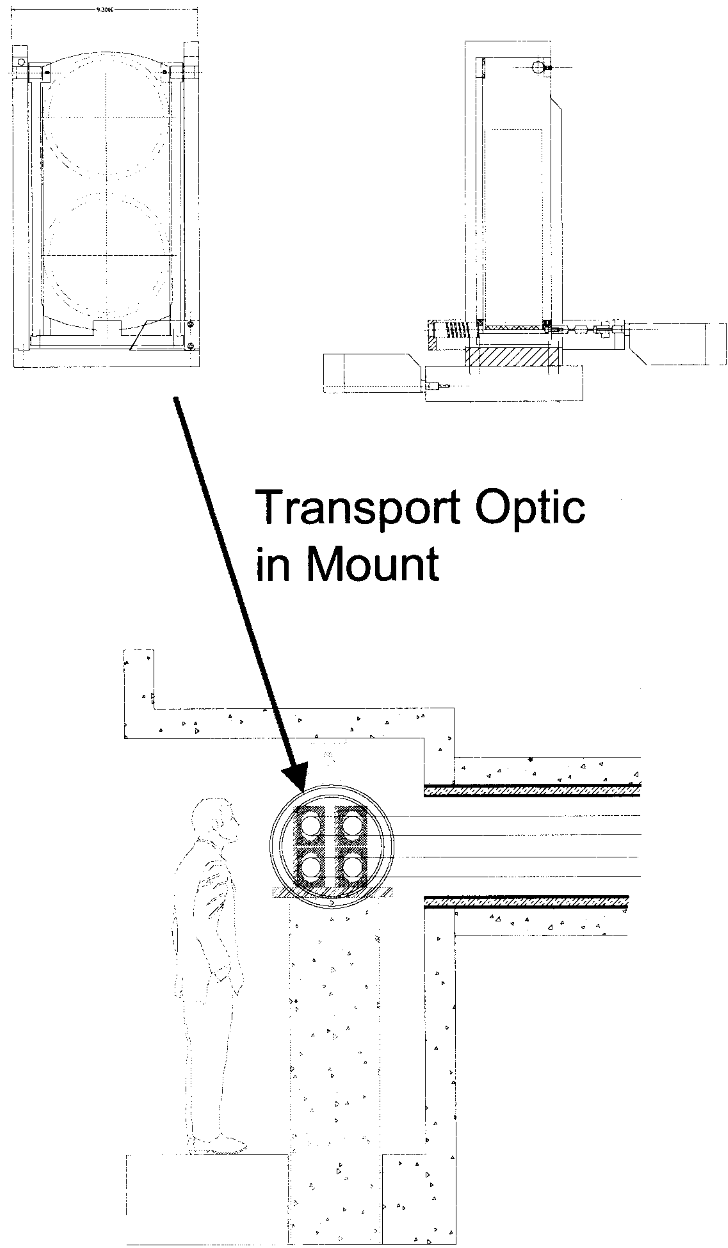
- Transport Optics
  - 2 reflections for Kecks, 2-4 for outriggers
- Long delay line (LDL)
  - 0-170m of static delay



- Fast delay line (FDL)
  - 0-20m of dynamic delay
  - 4:1 beam compression
- Switchyard
  - Redirects light to 2 um fringe tracker, nuller, 6-way imager, angle tracker
- Autoaligner

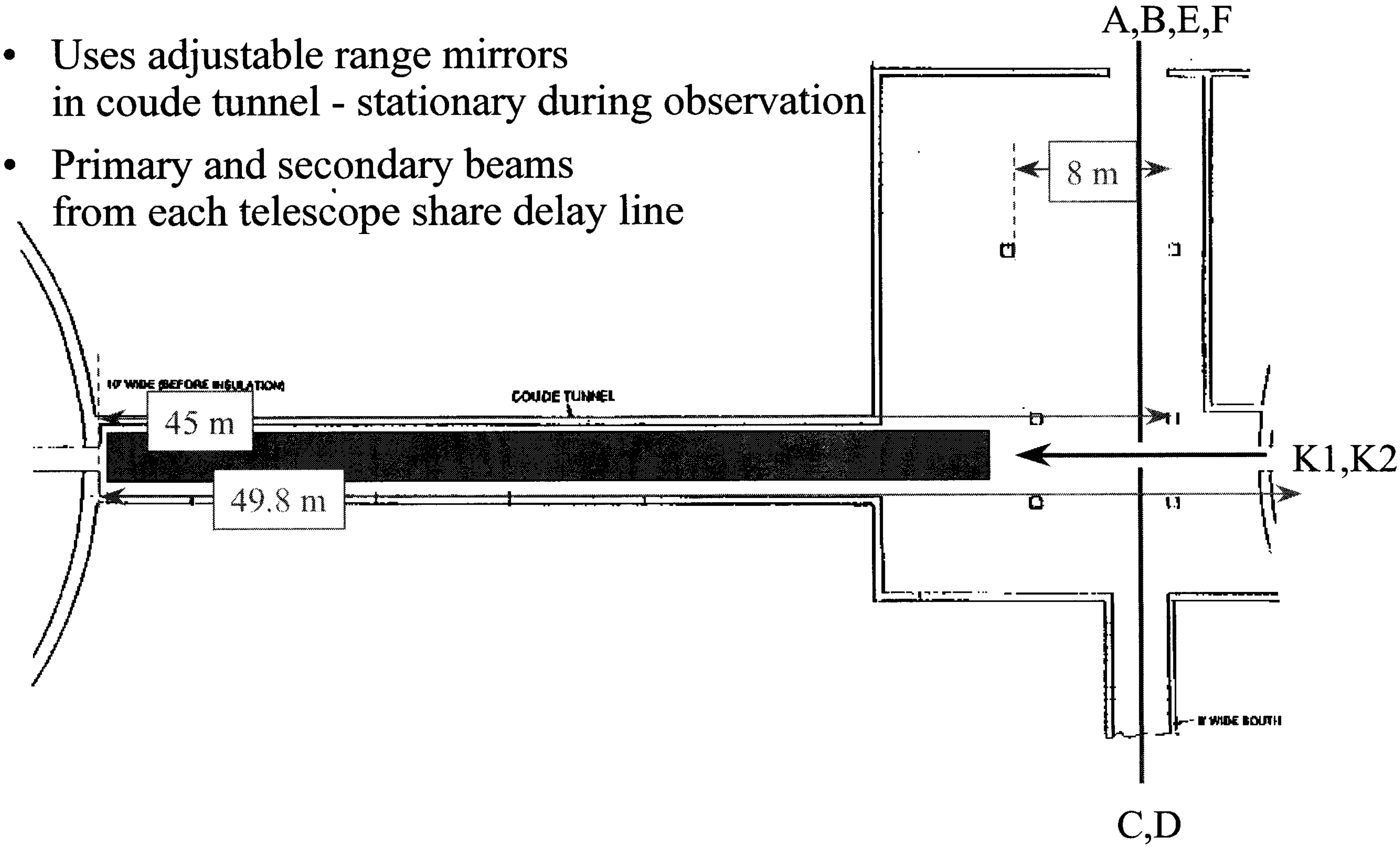
Transport Optics

- Requirements
  - Relay primary/secondary starlight clear apertures from end of coudé train to beginning of LDL
  - 146mm oversize for two 100mm starlight beams
  - Most mounts in TO train actuated for autoalignment system
  - Maintain polarization / image rotation budgets
- Derived specifications
  - 176mm center-to-center beam spacing
  - 90% clear aperture mirror at 45° means 355mm x 227 mm mirrors



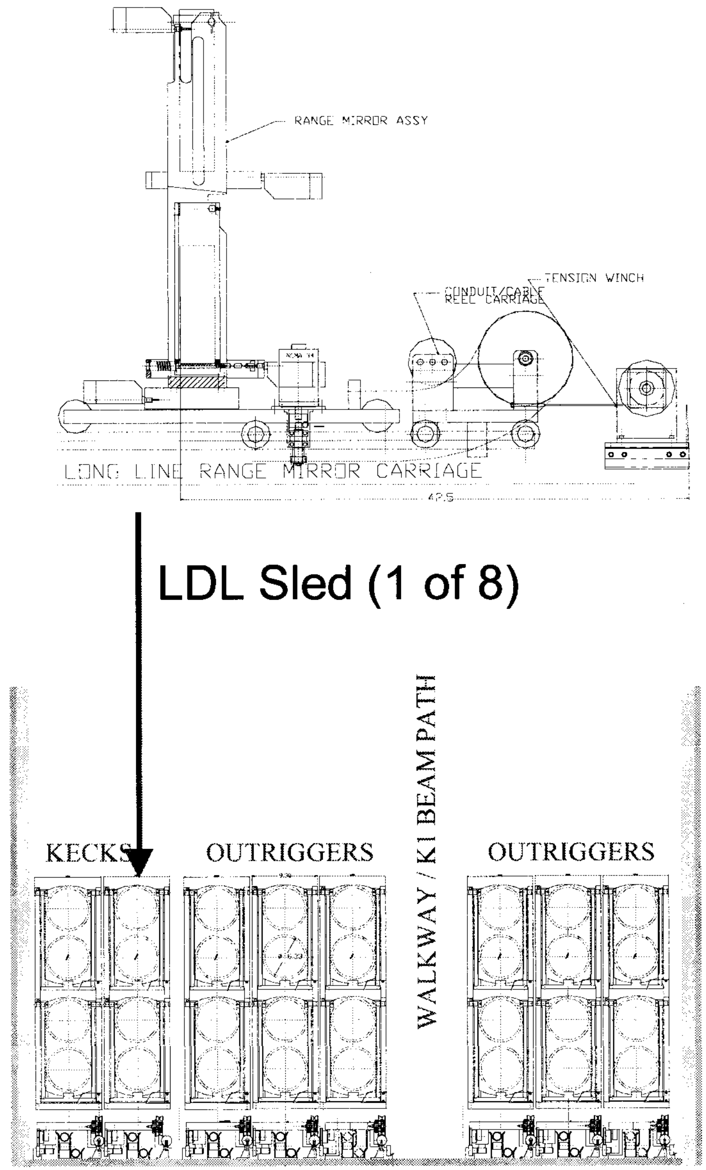
Long Delay Lines

- Uses adjustable range mirrors in coude tunnel - stationary during observation
- Primary and secondary beams from each telescope share delay line



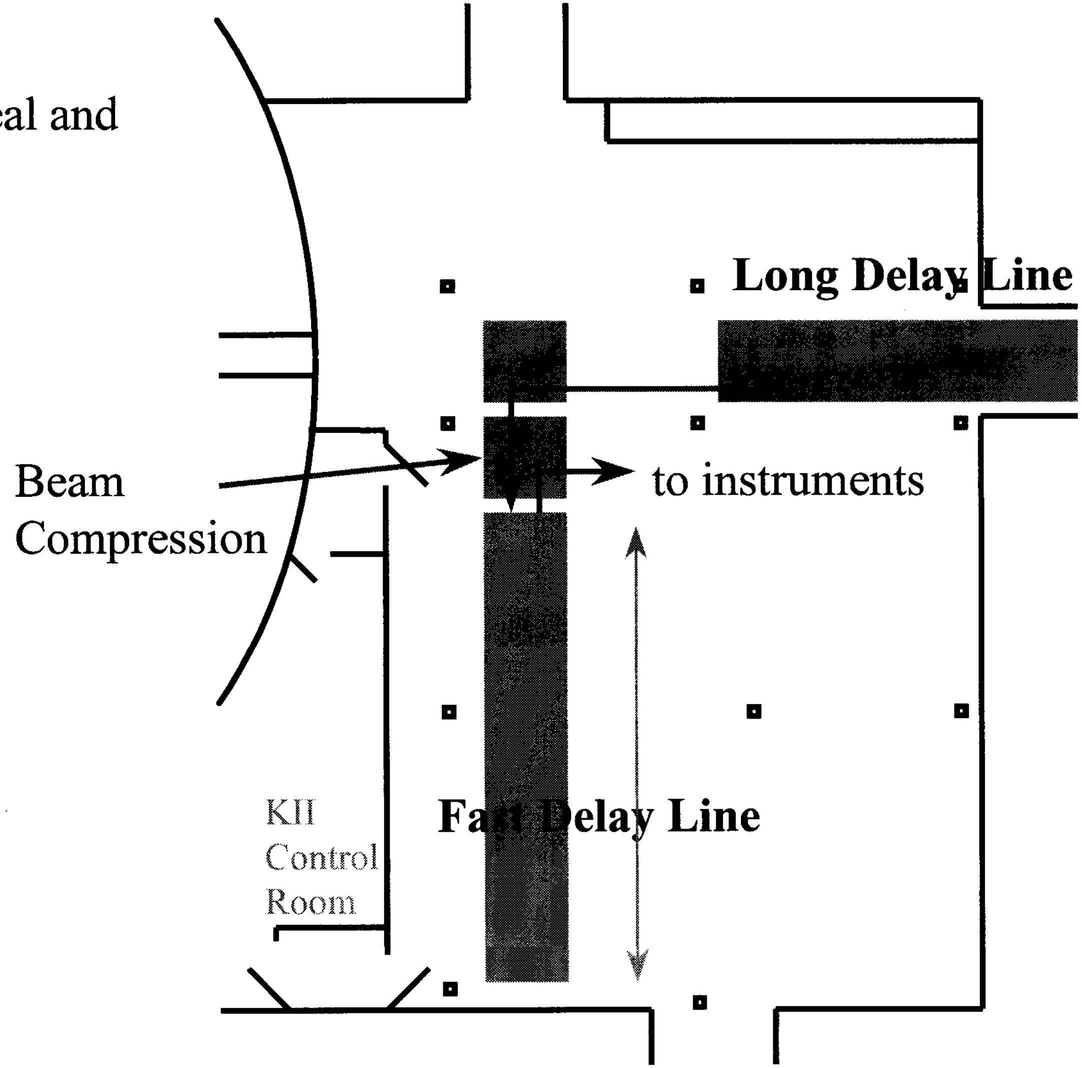
Long Delay Line

- Requirements
  - Accept light from TO, output split starlight beams to FDL
  - Provide 0-170m of delay for up to 8 telescopes
  - 1 mm knowledge of position
  - Fit in coudé tunnel
  - Move/realign with a telescope pointing/acquire time (1 min move, 3 min realign)
- Design
  - Two 355mm x 161mm mirrors on a common mount
  - LDL sleds are stripped-down FDL carts



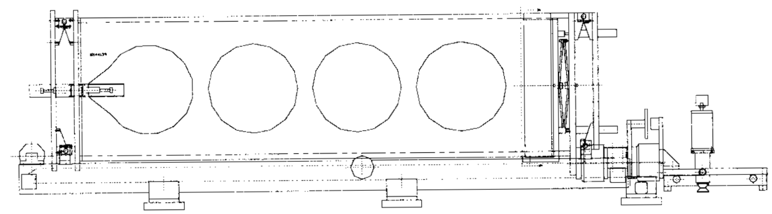
Fast Delay Lines

- Continuous tracking of sidereal and atmospheric motion
- PTI-type 4-stage design
- One per beam
- 20-m delay range

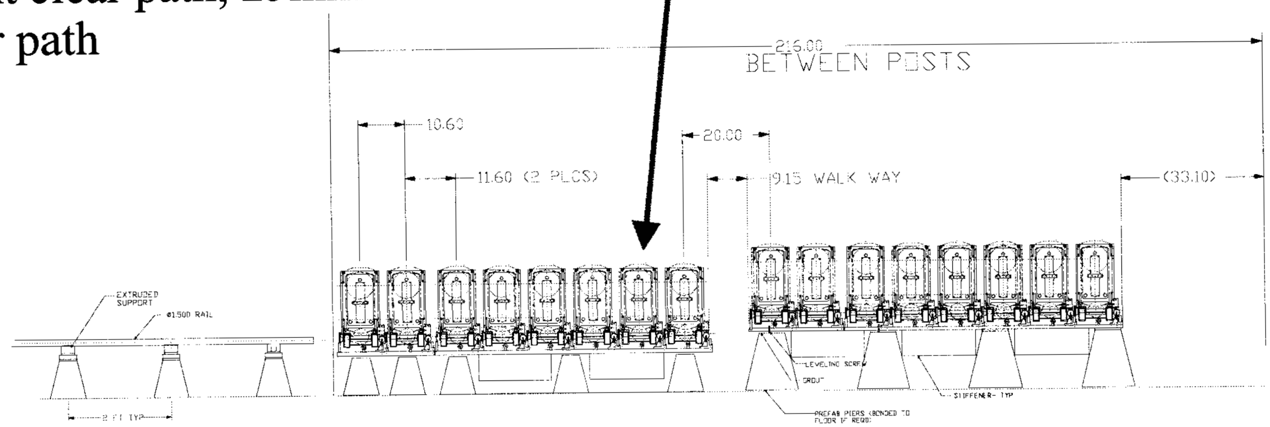


Fast Delay Line

- Requirements
  - Accept light from LDL, output 4:1 compressed beam to Swyd
  - Provide 0-20m of delay for up to 16 starlight beams
  - Jitter requirement: 10nm rms control
  - Accept handoffs at up to 5 kHz
- Design
  - Standard 4-stage design
  - 146mm starlight clear path; 25mm metrology clear path



FDL Cart (1 of 16)



Switchyard and stimulus

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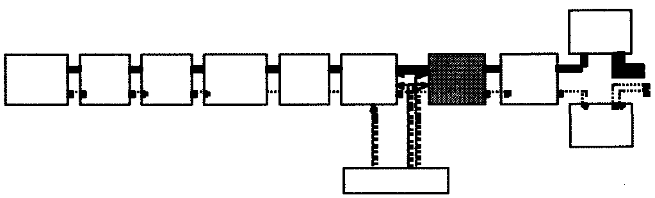
CreationDate: Thu Aug 28 19:17:48 1997

- Switchyard: accepts 12 delayed starlight beams and directs to beam combiner for desired mode
- Stimulus: star simulator to test all starlight subsystems



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Laser Metrology

- Three types
  - Local metrology of delay lines for servo control
  - End-to-end metrology of optical path for astrometry and cophasing
  - Accelerometer sensing of common-mode telescope optics

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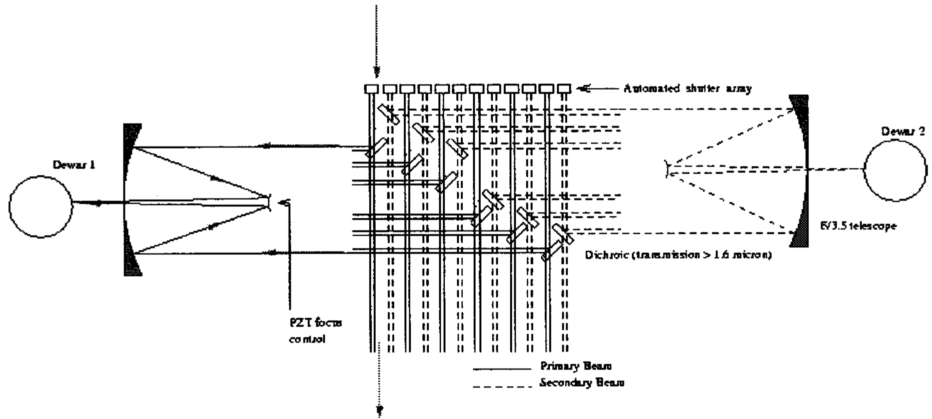
Angle Tracker

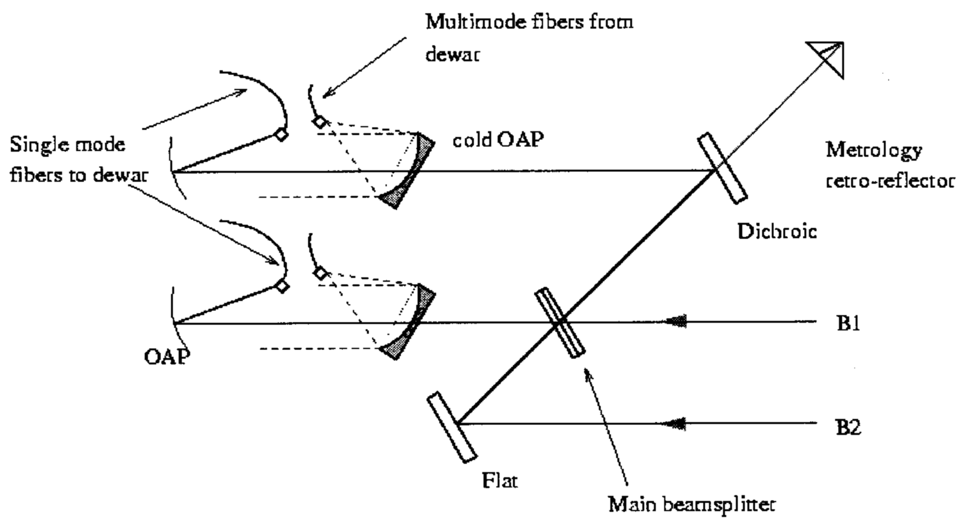
- For outriggers
  - Primary (high bandwidth) and secondary (low bandwidth with feedforward)
  - Correction via active secondary
- For Kecks
  - Track offsets to AO system
- Sensor
  - J-band infrared array
  - Separate dewars for primary and secondary stars



ANGLE TRACKER LAYOUT

Cophasing (2 μm) combiner

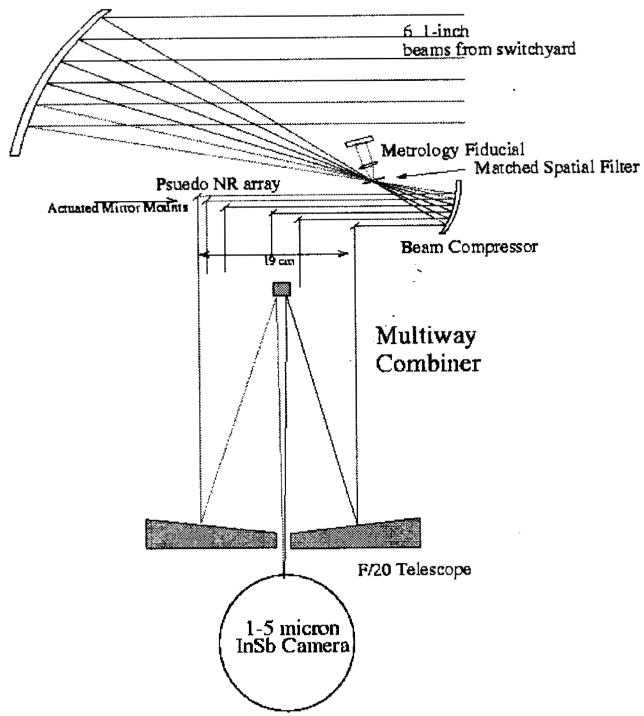
- Provide 5 two-way 2-μm combiners to support
  - Cophasing at H&K
  - Astrometry primary
  - Astrometry secondary
  - Single-baseline science
- Use low-noise FPA with fast reac capability like PTI
- Uses two fiber-fed dewars



Two-Way Combiner

Multi-way science combiner

- Pair-wise measurements on up to 15 baselines simultaneously
- Non-redundant cross-dispersed image-plane combiner
- 1.6--5.0 μm coverage with mid-wave MCT array
- 10 μm coverage with 10-μm nulling camera



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10 μm Nulling combiner

- Primary instrument for exozodiacal characterization
- Fast, switchable nulls on two spatial scales
- 10-μm infrared array camera

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Title:  Keck_nuller
Creator:  fig2dev Version 3.1 Patchlevel 2
CreationDate:  Tue Aug 26 11:26:23 1997
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Operating Modes

- Nulling for exozodiacal characterization
- Two-color differential-phase measurement
- Astrometry for detecting exoplanets
- Cophased imaging with 4, 5, or 6 telescopes

Exozodiacal dust and the Terrestrial Planet Finder

- For direct detection of exoplanets with TPF, the one unavoidable noise source is thermal emission of dust around the target star
- For our own solar system, the dust in the inner solar system will emit more 10-μm radiation than an Earth by a factor of ~50
- Exozodiacal dust adds noise; structure in dust adds spurious signatures
- Ground-based interferometric measurements can be used to identify low-dust system for observation by TPF

SNR for exozodiacal signal

- Features of the exozodiacal problem at 10 μm
  - Strong light from central star
  - Relatively weak exozodiacal signal
  - Strong 10-μm background
- If background limited, SNR is good

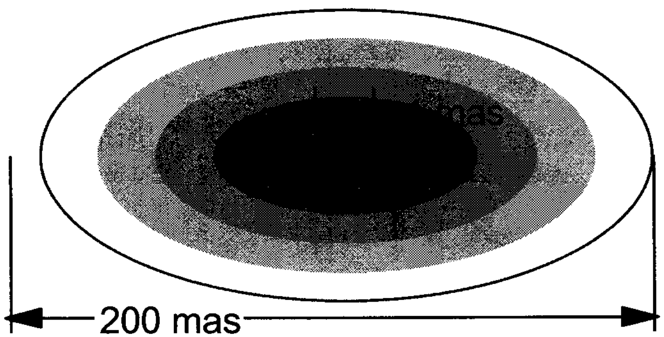
	flux (photons/sec)
Star at 10 pc	**1.5e8**
Background	**7.0e10**
Exozodi (10 x solar sys)	**1.3e5**
SNR in 1 hr	**15**

- $\lambda = 10\ \mu m$, $\Delta\lambda/\lambda = 0.3$
- emissivity = 0.5, $A\Omega = 1\ \lambda^2$
- total system efficiency = 0.1

The 1σ upper limit in 1 hour of integration is ~0.7 solar-system equivalents

Measuring exozodiacal dust with nulling interferometry

- Use interferometry with fast-switched nulls on aperture and interferometer spatial scales
  - Switched nulls modulate signal w/o changing background
  - Different scales distinguish between star and exozodiacal signal
  - Single-mode spatial filter accommodates imperfect Strehl

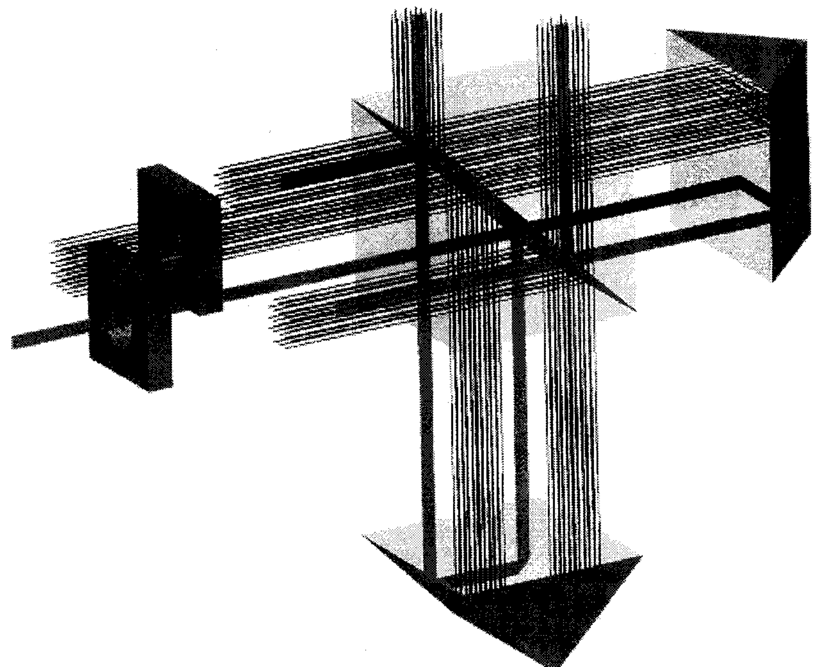


Target at 10 pc

- Two nuller scales at 10 μm
  - Aperture:
    λ / diameter = 200 mas
  - Interferometer:
    λ / baseline = 25 mas

Achieving an achromatic null

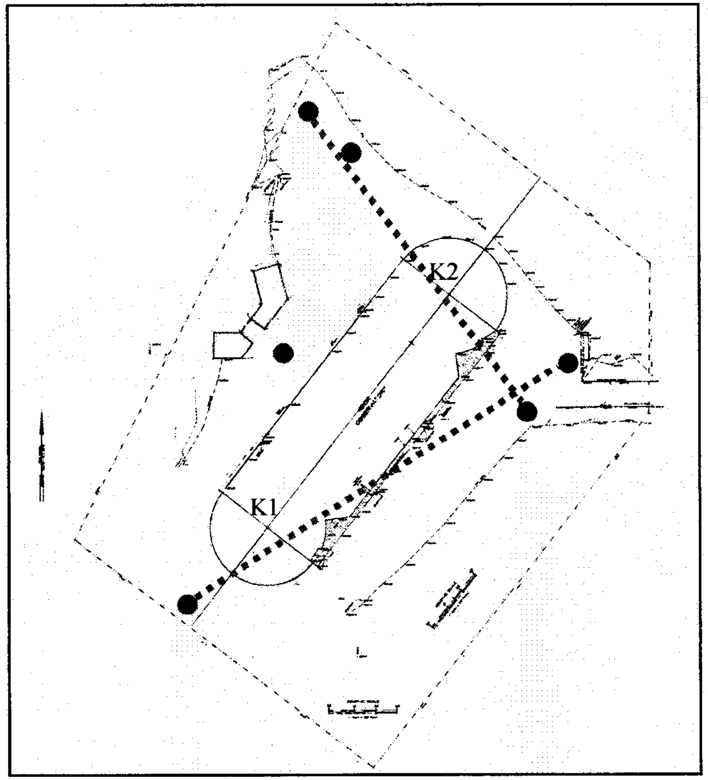
- Use Achromatic Nulling Interferometer (ANI):
  - ANI is an all-reflective, broadband, rotational shearing interferometer
  - Destructive interference at fringe center provides a deep 'null'



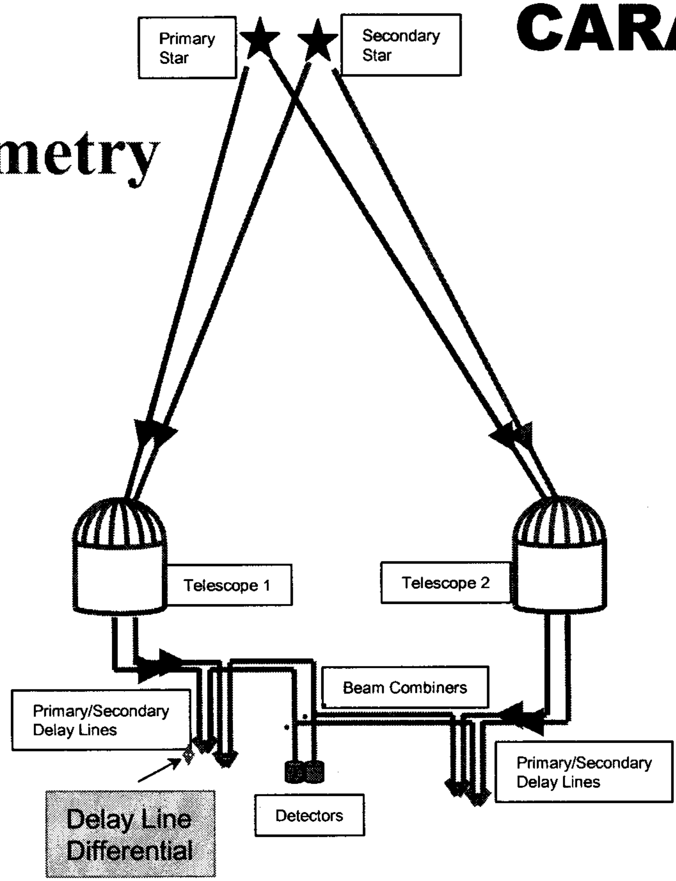
ROTATIONAL SHEARING INTERFEROMETER - 2 PUPILS

Astrometry

- Scientific objectives
  - Astrometric detection of planetary systems
  - Characterization of those planetary systems (specifically, multiple component systems)
- Specific questions to be answered
  - What is the relative frequency of planetary companions?
    - » Both in general and as a function of specific parameterizations (e.g., spectral type)
  - What is the nature of the planetary formation process?
  - Is our own solar system typical or atypical?



Dual Star Astrometry



- Primary star
  - Used to phase individual apertures
  - Used to cophase the interferometer
- Secondary star
  - Can integrate upon
  - Used as positional reference for primary star
- Delay line difference
  - Serves as measure of angular separation between stars
  - Angular separation can reflect periodic reflex motion of stars due to planetary companions
- Reference star limitations
  - Must be within one isoplanatic patch (~20" radius on the sky)
  - Photon noise contributes to overall error

Astrometric Observing

- Statistically significant target sample desired
  - 80 stars down to Uranus mass, 250 stars down to Jupiter mass
    - » Uranus/Jupiter masses show 25/125 μ as signal, respectively
  - Achieves two important goals for spectral types A, F, G, K & M:
    - » uncertainty in inferred planetary frequency rate 0.06 - 0.15 by subset
    - » P > 0.75 for planetary detection within a subset (> 0.999 for G, K, M)
- Proposed program: 50% of the outrigger observing
  - Delivers ~775 hours of observing annually
    - » 10 hours/night, 1/3 lost to weather, 20% time for calibration, 20% time lost due to instrument unavailability
  - Need two reference stars per astrometric target to isolate signatures
  - Need 4 observations per star annually
    - » Large Jupiter sample can be done quickly (~1/3 of the total time)
  - Options for greater throughput being explored
    - » E.g., one reference star per baseline per astrometric target

Astrometric Requirements

- Astrometric performance
  - Requirement: 30 μ as/$\sqrt{}$hr
  - Goal: 19 μ as/$\sqrt{}$hr - would allow doubling of primary sample
- Reference star brightness: $m_K \leq 17.2$
  - Sharp dropoff in star counts for $m_K < 17$ compounded by need for two nearby reference stars
  - Drives requirement for 1.8m telescope apertures
- Target star brightness: $m_K \leq 8.5$
  - Majority (>97%) of nearby stars out to 32 pc
- High throughput
  - 3 minutes star-to-star (15° field) 'dead time'
- Metrology-contiguous FOV
  - 15° radius - needed to find reference stars

Two-Color Phase-Reference Interferometry

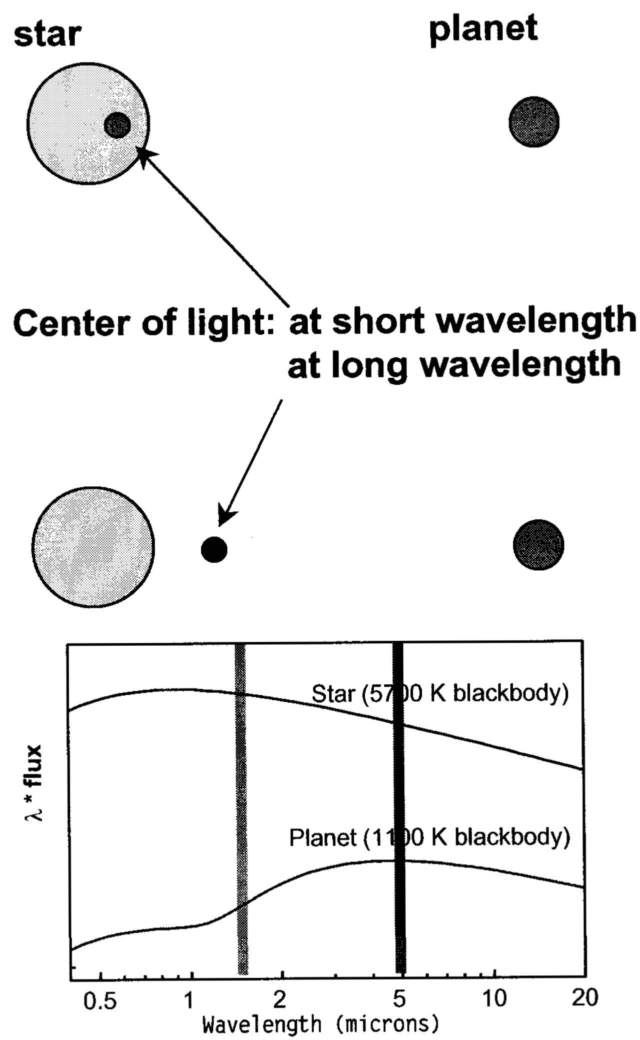
- Scientific objectives
  - Direct detection of warm jovian planets
    - » Includes orbital characterization → measuring the mass
  - Spectroscopic characterization of those planets
- Specific questions to be investigated
  - The same ones as astrometry, *in addition to:*
  - What is the nature of warm jovian atmospheres?
    - » Can compare to data on Jupiter/brown dwarfs/stars

Known Warm Jovians

Star	Orbit (AU)	T (K)	Sep. (arcsec)
HD 114762	0.40	475	0.014
υ And	0.05	1300	0.003
τ Boo	0.05	1400	0.003
55 ρ Cnc	0.11	900	0.008
16 Cyg	1.72	230	0.08
51 Peg	0.06	1200	0.004
70 Vir	0.43	450	0.019
ρ CrB	0.23	625	0.014
47 UMa	2.10	200	0.16

Detecting Warm Jupiters with Two-Color Observations

- Two-color phase referencing
  - Short wavelength: phase reference
    - » center of light close to star
  - Long wavelength: science measurement
    - » center of light displaced towards planet
  - Phase difference is observable
    - » use adjacent bands on one detector
    - » very insensitive to systematics
- GL229B: significant changes in flux ratio just between 1.6 & 2.2 μ m



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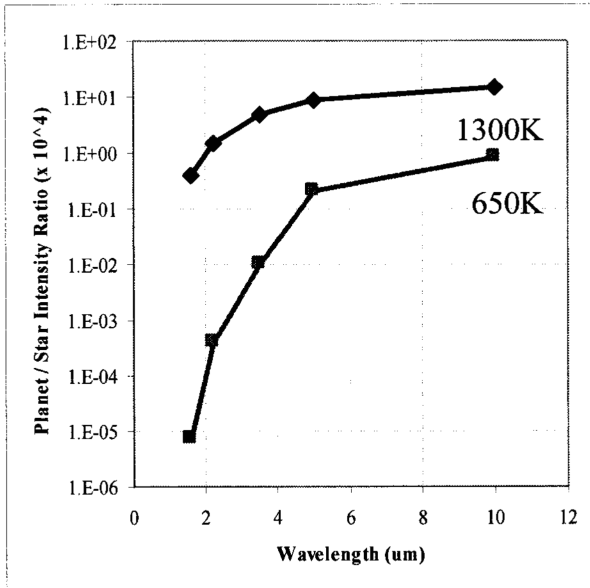
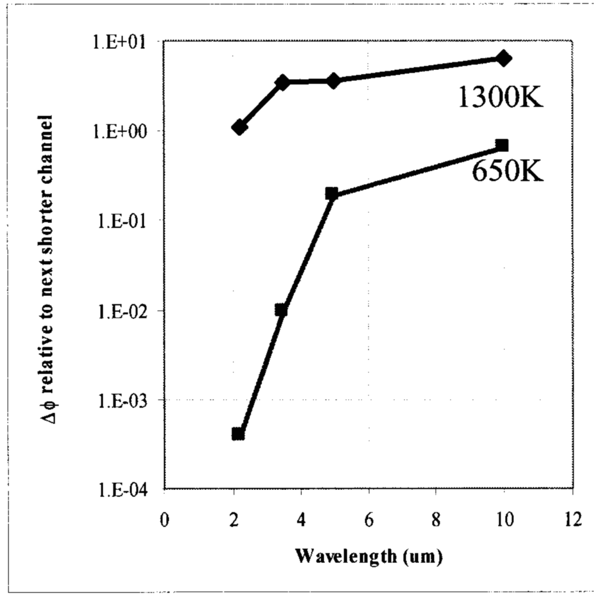
Signal-to-Noise Ratio for Detecting Warm Jupiters

- H-K Example
  - 1300K planet
  - $\Delta\varphi_K = 1.11\times10^{-4}$ rad
  - Requires SNR= 10^4
  - For m_K= 4.0, SNR = 2000 in 10 ms → 0.25 s
- M-N Example
  - 650K Planet
  - $\Delta\varphi_M = 0.63\times10^{-4}$ rad
  - Requires SNR=1.6×10^4
  - For m_M= 4.0, SNR = 700 in 10 ms → t = 6 s





Wavelength (μm)	1300 K Planet (51 Peg)		650 K Planet (ρ CrB)	
	Planet/Star Intensity Ratio (x 10^4)	Δφ relative to next shorter channel	Planet/Star Intensity Ratio (x 10^4)	Δφ relative to next shorter channel
1.6	0.39		0.000	
2.2	1.50	1.11	0.010	0.01
3.5	4.90	3.40	0.200	0.19
5	8.50	3.60	0.830	0.63
10	15.00	6.50	3.400	2.57

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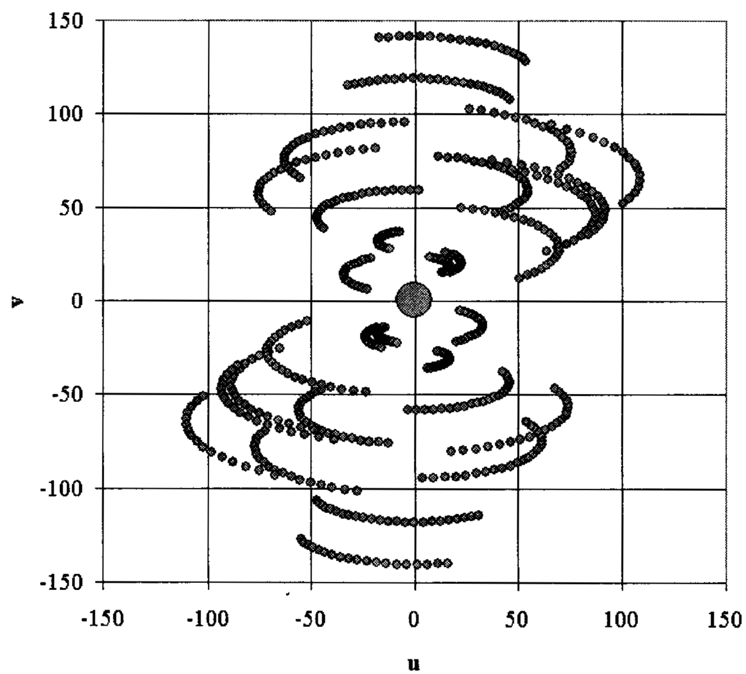
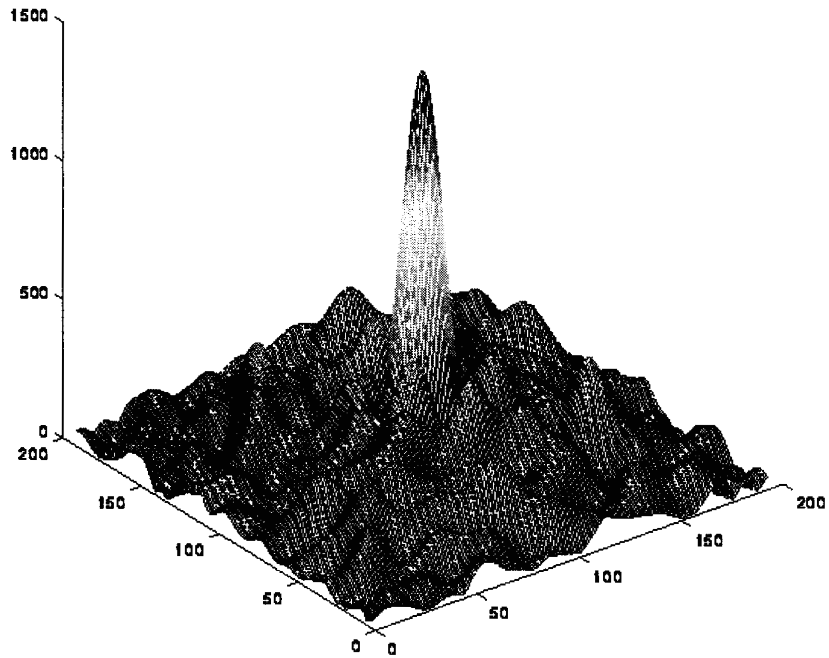
(u,v) coverage and raw PSF



6 telescopes, one night
source at 19 deg decl.



Angular resolution: 3 mas @ 2.2 μm
10 mas @ 10 μm

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Expected Performance (NGS)

On-axis Full Array Cophasing Limit:		4 Outriggers	1 Keck + 4 Outriggers		2 Kecks + 4 Outriggers		
		2m / 2m	*10m / 2m*	*2m / 2m*	*10m / 10m*	*10m / 2m*	*2m / 2m*
2.2 um		11.0	12.8	N/A	15.0	12.9	N/A

Off-axis Limit:	Astrometric	4 Outriggers	1 Keck + 4 Outriggers		2 Kecks + 4 Outriggers		
	2m / 2m	*2m / 2m*	*10m / 2m*	*2m / 2m*	*10m / 10m*	*10m / 2m*	*2m / 2m*
1.6 um	N/A	19.1	21.2	19.0	23.5	21.0	18.8
2.2 um	17.0	18.2	20.1	18.0	22.1	20.0	17.9
3.5 um	N/A	13.5	15.3	13.3	17.1	15.1	13.2
5 um	N/A	11.0	12.7	10.8	14.5	12.6	10.7
10 um	N/A	7.5	9.2	7.3	10.9	9.1	7.2

SNR=10 for cophasing, K only
SNR=10 per baseline in 1000 sec for imaging
SNR=72 in 3600 sec for astrometry

Artist's conception of Keck Interferometric Array showing outrigger telescopes